Monitored Ground Source Heat Pump Performance in Northern California

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ABSTRACT

Fourteen residential ground source heat pump installations in the greater Northern California area were monitored during the period of December 1996 to January 1998. Equipment power, capacity, and efficiency, and loop water temperatures and flow were recorded on a 15 minute basis. Monitoring results were used to calibrate the DOE2.1E hourly building simulation program ground loop model and DOE2.1E was then used to estimate energy savings and life cycle economics for various load, system, and installation configurations.

Introduction

Ground source, or geothermal, heat pumps (GHP's) utilize a closed loop of tubing buried in the ground to exchange heat with the soil instead of the refrigerant-to-air outdoor coils used by conventional air-source heat pumps (AHP's). GHP's typically have higher operating efficiencies than AHP's due to milder condensing and evaporating temperatures, elimination of defrost cycles, and little or no need for supplemental resistance heating during cold weather. Since GHP systems lack the outdoor compressor/fan unit they are quieter than AHP's. GHP systems are in widespread use in the north-central and southern states, but are relatively new to the West, where this study was conducted.

To verify GHP market viability in their service territories, the Sacramento Municipal Utility District (SMUD) and the Truckee-Donner Public Utility District (TDPUD) obtained funding from the California Energy Commission to conduct a GHP field monitoring project. Both SMUD and TDPUD have pioneered GHP market development in California by providing direct incentive payments, organizing bulk purchase programs, and facilitating infrastructure development.

SMUD is an electric utility serving customers in Sacramento County, in the central valley of California. The utility is summer peaking with residential air conditioning a principal contributor to the peak load of 2,250 MW. Summers are typically hot and dry with summer temperatures exceeding 100°F about 20 times a year. Winters are relatively mild with low temperatures rarely falling below freezing (2,840 HDD). Outlying areas of SMUD service territory do not have natural gas service and are therefore prime candidates for GHP technology.

TDPUD is an electric and water utility serving 10,000 customers in the Sierra Nevada, approximately 30 miles west of Reno, Nevada. At an elevation of 6,000 feet, the area has cold winters (8,230 HDD) with a winter peak utility load of about 28 MW. Nighttime temperatures below 0°F are not uncommon, although winter days are generally sunny. Summers are mild and dry with few days exceeding 90°F. Natural gas, though nearly as costly as propane, is available in urban areas. The frequent use of wood fuel for heating, substantially compromises winter air quality in the Truckee area.

Objectives

The principal project objective was to determine GHP energy and demand savings relative to conventional system types in both SMUD and TDPUD service territories. This information could then be used to determine utility and customer value and determination of overall cost-effectiveness.

Methodology

The basic approach was to develop and implement a monitoring plan which would provide detailed equipment and ground loop performance data to allow for modifying the DOE-2.1E building simulation program ground source model. This calibrated model could then be used to develop performance projections under various building load, climate, and equipment efficiency scenarios.

Specific project tasks included:

- Develop a detailed monitoring plan
- Select candidate sites and procure monitoring hardware
- Install and commission 14 monitoring sites
- Collect, reduce, and analyze data over a 14 month period
- Evaluate monitoring data to characterize equipment and ground loop performance at each site
- Calibrate the DOE-2.1E ground source heat pump model
- Complete DOE-2.1E parametric evaluation for a range of scenarios

System Monitoring

A brief characterization of the 14 sites is included in Table 1. Data collected at all sites included temperature, energy use, and ground loop flow. Air flow rates were determined using one-time flow hood measurements; all other data were continuously recorded. Sensors were scanned on 15 second intervals and were averaged or totaled and logged at 15 minute intervals. Energy transfers between the heat pump and the ground loop, and between the heat pump and the house were computed from mass flow rates and temperature differences on a 15 second basis.

The TDPUD sites were commissioned in December 1996 and most of the SMUD sites were commissioned by February 1997. Routine data acquisition commenced as soon as site commissioning was completed. Data were downloaded on a nightly basis, and were promptly reviewed to identify out-of-range readings resulting from power outages or failed sensors.

Table 1. Description of GHP Monitoring Installation Sites

Site	Construction Type	Conditioned Floor Area (ft^2)	Nominal GHP tons	Vertical Bore (ft/ton)
TDPUD Sites				
T1	Retrofit	2500	4	200
T2	New	3500	5	180
T3	Retrofit	1230	3	160
T4	Retrofit	1250	3.5	114
T5	Retrofit (B&B Inn)	3580	5 + 3	150
SMUD Sites				
S1	New	2910	5	200
S2	Retrofit (office)	550	2.5	200
S3	Retrofit	2060	4	170
S4	Retrofit	2260	4	(1)
S5	Retrofit	1700	2.5	(2)
S6	New	2540	5	200
S7	Retrofit	2620	4	(3)
S8	Retrofit	2400	5	240
S9	New	1260	3	133

Notes:
(1). Horizontal single-pipe: Five 500' trenches, 15' apart, 2-3' deep.
(2). Vertical slinky: Three 90' trenches, 3000' pipe, 1-4' deep.
(3). Vertical helix: Five 30" diameter helix coils, 20' deep.

Modeling Approach

A primary project goal was to utilize detailed GHP system monitoring data to generate inputs to be used for calibrating the DOE-2.1E computer simulation. DOE-2.1E was selected as the simulation tool for this study because it is the most widely utilized building simulation program with the capability to simulate GHP system operation on an hourly time step. Hourly simulation is far superior to simpler modeling techniques such as bin methods, because interactive system/load effects can be accounted for and ground loop performance can be predicted with much greater accuracy.

A matrix of simulation cases was developed to generate GHP performance projections relative to conventional system alternatives. "Typical" and "High" load cases were developed by varying thermostat setpoints and schedules to assess the sensitivity of the results to variations in building load. Parametric evaluations were used to assess the impact monitored variations in GHP and ground loop performance have on results. To achieve this, worst and best case performance scenarios were developed. The "worst" case combined poor ground loop performance with poor heat pump performance. The "best" case scenario was defined in a corresponding manner.

The most common conventional heating system in the TDPUD area is a natural gas or propane furnace. Base case runs for both standard efficiency gas furnaces (78% AFUE) and high efficiency condensing furnaces (92% AFUE) were performed. In SMUD service territory, base case systems are typically 78% AFUE gas furnaces with 10 SEER air conditioners (Gas/AC), however air-source heat pumps (AHP's) are also common in the retrofit market and in more rural areas of SMUD territory where natural gas in not available. Three separate base case system types were simulated for SMUD:

- Standard Gas/AC case (78% AFUE furnace/10 SEER AC)
- High efficiency cooling Gas/AC case (78% AFUE furnace/12 SEER AC)
- Standard AHP case (6.8 HSPF/10 SEER AHP)

SMUD tiered electric rates (average winter and summer cost of $.095 and $.104/kWh, respectively) local natural gas rates, and TDPUD utility rates of $1.07 per therm and $.06061/kWh were used.

Table 2. DOE-2.1E Modeling Cases

	Building Loads	GHP	Ground Loop
TDPUD Cases			
Gas - 78% AFUE	M, H	N/A	N/A
Gas - 92% AFUE	M	N/A	N/A
GHP (Vertical loop)	M	W, T, B	W, T, B
"	H	T	T
"	M, H	T	T
SMUD Cases			
Gas/AC - 10 SEER	M, H	N/A	N/A
Gas/AC - 12 SEER	M	N/A	N/A
AHP - 6.8 HSPF	M	N/A	N/A
GHP (Vertical loop)	M	W, T, B	W, T, B
"	H	T	T
"	M, H	T	T

Note:
For loads, "M" = medium, "H" = high
For GHP and ground loop, "W" = worst, "T" = typical, "B" = best

A 1700 ft^2 single-family home was selected as being representative of the target GHP market. Working with both utility project managers, DOE-2.1E input files were modified to make them representative of typical new construction in each location. ACCA Manual J sizing[1] was then performed on these prototypes to size equipment.

GHP performance data from each of the 14 sites were evaluated to develop appropriate inputs for DOE-2.1E. DOE-2.1E models GHP systems by adjusting ARI-330[2] rated full-load capacity and electric-input-ratio (EIR) using biquadratic curves which account for variations in return water temperatures and indoor air at non-ARI-330 conditions. (EIR is defined as the non-dimensional ratio of electric power input to the total heating or cooling capacity of the unit, and is the inverse of COP.)

[1] Manual J is the standard residential load calculation method published by the Air Conditioning Contractors of America.
[2] ARI-330 is the American Refrigeration Institute test method used for closed-loop ground-source heat pumps.

Calculated hourly steady-state performance is then modified by a curve which accounts for part-load affects, or cycling performance, of the equipment. The ARI-330 heating rating condition is 70°F entering air temperature and 32°F return water temperature; cooling rating conditions are 80°F entering air dry bulb temperature and 67°F entering air wet bulb, and 77°F return water temperature. Full-load monitoring data from each site were plotted versus the independent variables and regression analysis was performed to determine sensitivity to the independent variables.

The ground loop model used by DOE-2.1E was developed in 1995 by Dick Merriam at Arthur D. Little Company. The model calculates hourly loop return water temperatures based on the energy transfer to the ground, loop configuration, and soil parameters. Since understanding and characterizing ground loop performance was one of the key project goals, DEG extracted and re-compiled the DOE-2.1E loop model to allow loop calibrations to be performed independent of DOE-2.1E. Monitored loop flow rates, GHP operating patterns, and heat rejected/extracted from the ground were combined with known loop parameters and estimated soil characteristics to allow the model to project hourly return water temperatures. Key inputs (pipe/grout conductivity, deep ground temperature, and average soil conductivity) were varied within reasonable ranges in an effort to obtain the best correlation with monitored data. Minimizing the Chi-squared difference between monitored and modeled return temperatures defined the "best-fit" ground loop calibration for each site.

Results

Monitoring Data Summary

Table 3 summarizes total GHP space conditioning energy use, including pump and auxiliary resistance heat, for the 12 month period from February 1997 to January 1998. Data taken from TDPUD sites during December 1996 and January 1997 are not included in the table to facilitate an annual use comparison. SMUD sites S4, S6, S7, S9 were not monitored for the full 12 month period, affecting the annual energy totals presented in Table 3.

Variations in usage, due to location, building design, and occupant comfort preferences, cause TDPUD sites to vary from a low of 1.5 kWh/ft^2-year (T2) to a high of 6.8 kWh/ft^2-year (T1). Site T5, a bed and breakfast inn, was the only TDPUD site to use any significant cooling energy. Energy use for those SMUD sites for which a full year of data were taken ranges from a low of 0.5 kWh/ft^2-year (S1) to a high of 2.6 kWh/ft^2-year (S2). A significant factor affecting TDPUD heating energy use was the level of solar access for the site. Site T2 was designed as a passive solar house and demonstrated the lowest energy use. In contrast site T1, which is surrounded by tall trees, had per ft^2 energy use 4.5 times higher. In the milder SMUD climate, annual heating and cooling energy use is much more strongly dictated by homeowner thermostat control than by envelope thermal quality. For example, of the three residential new construction sites, two represent the lowest energy users (S1 and S9) and the third represents the highest residential user (S6).

A performance advantage often attributed to GHP systems is the more moderate condensing/evaporating temperatures compared to air source equipment. In addition, the refrigerant-to-water heat exchanger used by GHP's have improved heat transfer characteristics which result in an approximate 50% fluid-to-refrigerant delta-t reduction when compared to refrigerant-to-water heat exchangers. Average winter season return water temperatures for the TDPUD sites ranged from 27 to 40°F, or about 2°F warmer than the coincident outdoor air temperatures. Average SMUD return water temperatures ranged from 45 to 61°F in winter (~5°F warmer than coincident outdoor air) and 78 to 95°F in summer (~4°F cooler than coincident outdoor air).

Table 3. Monitored Energy Use Summary

Site	Data Period	Monitored Annual[1] Energy Use (kWh)	Normalized Energy Use (kWh/ft^2-year)
TDPUD Sites			
T1	Feb 97 - Jan 98	17037	6.8
T2	Feb 97 - Jan 98	5334	1.5
T3	Feb 97 - Jan 98	3659	3.0
T4	Feb 97 - Jan 98	5387	4.3
T5	Feb 97 - Jan 98	9467	2.6
SMUD Sites			
S1	Feb 97 - Jan 98	1533	0.5
S2	Feb 97 - Jan 98	1437	2.6
S3	Feb 97 - Jan 98	1800	0.9
S4	May 97 - Jan 98	5081	2.2
S5	Feb 97 - Jan 98	3583	2.1
S6	Mar 97 - Jan 98	6466	2.5
S7	Mar 97 - Jan 98	3154	1.2
S8	Feb 97 - Jan 98	5563	2.3
S9	Mar 97 - Jan 98[2]	1003	0.8

Notes:
(1) For months with partial data, energy use was calculated as *monitored use / available data fraction*
(2) No data available Dec '97

The monitored heating coefficient of performance (COP) ranged from 3.0 to 4.0 and averaged 3.5 for TDPUD sites. The COP range for SMUD sites was 3.3 to 4.6, with an average of 4.0. Cooling season energy efficiency ratios (EER's) for the SMUD sites ranged from 10.9 to 16.4 and averaged 12.8 kBtu/kWh. Heating COP's were higher than ARI-330 COPs for all but three sites. Cooling EER's were higher than ARI-330 ratings for about half the SMUD sites. Lower performance values can be explained by marginally sized ground loops in most cases.

Figures 1 and 2 present sample GHP demand plots for a peak TDPUD heating day and for the peak SMUD cooling day. Figure 1 shows monitored GHP demand at sites T1, T2, and T4 for January 6, 1998, when outdoor temperatures ranged from a low of 2°F to a high of 36°F. Site T1 demonstrated continuous demand from 12 AM to about 1 PM with some supplemental resistance heating (demand exceeding 4.2 kW is due to resistance heat). Site T2, with hydronic radiant floor delivery and load side storage, shows extended GHP operating cycles in response to the storage tank thermostat. The unit runs throughout the day with GHP on-time varying through the day as the building load decreases. Site T4 shows continuous operation through Noon, at which time the building load starts to decrease.

Figure 2 plots GHP demand for three SMUD sites on August 7, 1997 when outdoor temperature ranged from the low 70's to about 108°F. Sites S5 and S6 demonstrate operation in response to a thermostat as demand ramps up to a fairly constant mid-day level. The Site S7 profile is indicative of mid-day non-occupancy with extended cooling starting abruptly at 5 PM.

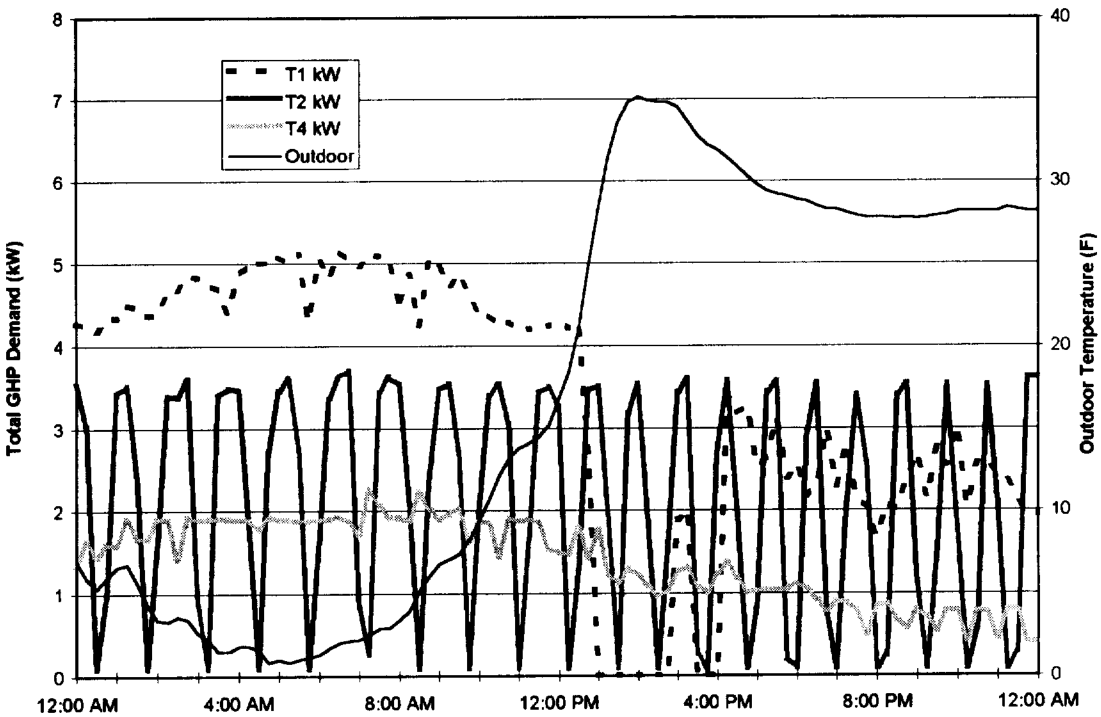

Figure 1. TDPUD Winter Day GHP Demand Profile

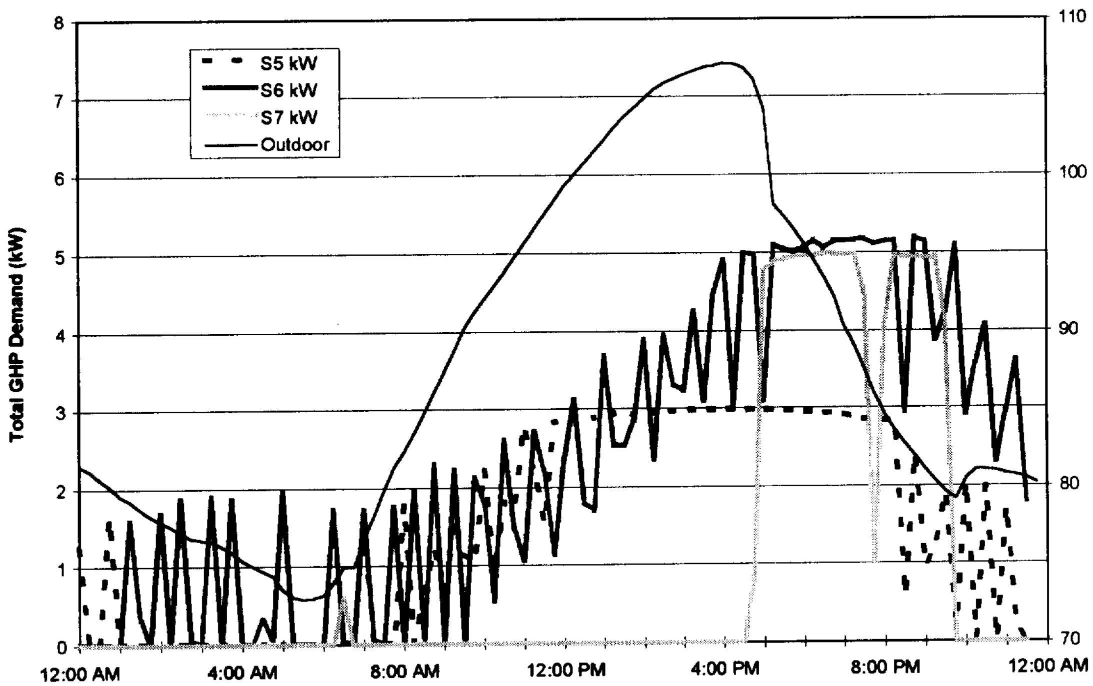

Figure 2. SMUD Summer Day GHP Demand Profile

GHP Performance Curves

To generate DOE-2.1E performance curves, full-load heating and cooling capacity and compressor efficiency data from each monitoring site were plotted against entering air temperature and ground loop return water temperature. These data were used to generate a "best fit" regression for each site. The regression lines were normalized to pass through 1.0 at the ARI rating condition for consistency with DOE-2.1E inputs. The regression analysis generally confirmed the reliability of using manufacturer's published performance data as "typical" performance in the DOE-2.1E simulations. For that reason, manufacturer's data was used to represent "typical" GHP performance. Individual equipment curves were also selected to represent "best" and "worst" expected equipment.

Ground Loop Calibration

Available ground loop data from each site was collected and converted from 15 minute monitoring format to one hour average data for compatibility with the ground loop model extracted from DOE-2.1E. The ground loop model requires description of the loop (number of bores, bore length, flow rate, etc.), an input file containing fractional GHP operation for each hour of the year, and hourly energy extracted from or rejected to the ground loop. This input data combined with the loop configuration and soil condition drives the loop model. In response to an hourly load, the model generates projections of return water temperature based on the above parameters. Input constants were varied to minimize the Chi-squared difference between monitored and modeled return water temperatures for each site.

In performing the calibrations for each site, it became evident that a good fit could be obtained without significantly varying the ground parameters (such as soil and pipe conductivity) from standard assumptions for the site. It was reassuring to find that fairly consistent results could be obtained for sites within a similar geographic region. Figure 3 shows a sample ground loop calibration result. Monitored and modeled return water temperatures are plotted against time of year for hours where the GHP operated for more than 60% of the hour. The daily variation in temperature in response to varying soil loading is matched well by the model, however hour-to-hour variations were typically understated by the model.

The principle inputs used for calibration were deep ground temperature and soil and pipe conductivity. The deep ground temperature essentially serves as an offset moving the calibration curve up and down. For example, increasing the assumed deep ground temperature by 3°F, would shift all the modeled data up by 3°F. Soil and pipe conductivity effect the hourly response of the model with the key effect of modifying the amplitude of response to a cooling or heating load. Because we were only monitoring the supply and return water temperatures there is no way to differentiate between the effect of pipe and soil conductivity. We adjusted soil conductivity within the range of expected values and only adjusted pipe conductivity if more adjustment was required. Both TDPUD and SMUD calibration results indicate fairly consistent calibration inputs among the various sites. Table 4 presents the averaged parameters used for the "typical" vertical loop performance projections in DOE-2.1E.

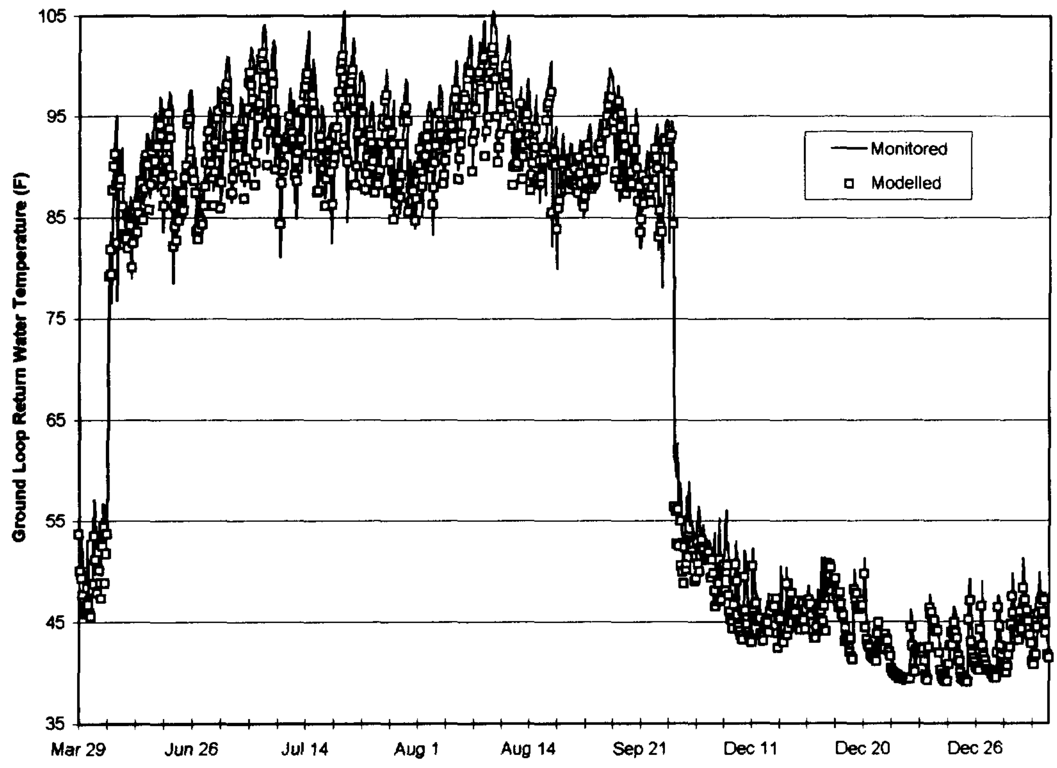

Figure 3. Ground Loop Calibration Results - Site S6

Table 4. Average Vertical Loop Calibration Results

Location	Deep Ground Temp	Soil Conductivity (Btu/hr-ft-°F)	Thermal Diffusivity (ft^2/hour)	Pipe Conductivity (Btu/hr-ft-°F)	Bore Spacing (feet)
TDPUD	43°F	1.40	0.040	0.226	20
SMUD	65°F	0.90	0.028	0.226	15

Because loop performance can be a function of many variables including loop sizing, soil conditions and moisture level, loop flow rate, and quality of the loop installation, deviations from typical loop performance were expressed solely in terms of a proxy "feet of loop per nominal ton". |Describing variations in terms of "feet per ton" quantifies the uncertainty in loop performance with a parameter that most in the GHP industry are familiar with. For both SMUD and TDPUD, the variation in loop performance was estimated to be ±25% from the typical case. Typical loop sizings were based on the average of the monitoring sites and defined as 160 feet/ton for TDPUD and 190 feet/ton for SMUD.

DOE-2.1E Performance Projections

To effectively bracket the efficiency range of existing GHP equipment for DOE-2.1E simulations, three ARI-330 listed GHP units were selected. Table 5 summarizes the ARI-330 values for the "typical", "best", and "worst" equipment selected. Since DOE-2.1E calculates indoor fan and loop pump power separately, Table 5 also includes input power assumptions for these.

Table 5. Nominal and Adjusted GHP Efficiency Inputs

Site	Listed ARI-330 Efficiencies Heating COP	Cooling EER	Pump Power Watts	Fan Power Watts/1000CFM
Typical	3.1	13.4	200	300
Best	3.3	15.7	200	175
Worst	3.0	10.9	200	400

Tables 6 and 7 summarize simulation results for TDPUD and SMUD, respectively. Miscellaneous ("Misc") energy use includes blower fan energy, crankcase heater energy, and GHP pump energy use. Listed peak demand for TDPUD is the average of the 4-6 PM GHP demand on an assumed 4°F winter design day. SMUD peak demand is the 2-8 PM average for the peak SMUD summer day.

For the TDPUD service area, projected GHP savings are roughly $710/year vs. a standard efficiency furnace and $480/year vs. a condensing furnace. The expected impact due to performance variations (best and worst scenarios) results in a ±$100 change in the expected savings. As building loads increase, the expected annual savings also increase. A favorable electric rate relative to high existing natural gas costs is the primary factor influencing these GHP economics.

Table 6. DOE-2.1E Performance Projections for TDPUD

System Type	Load Case	Loop Type	GHP Case	Heating therms	Annual Usage (kWh) Clg	Htg	Misc	Peak kW	Annual Cost($)
Gas - 78%	Med	N/A	N/A	1012	0	0	1021	0.3	$1538
Gas - 78%	High	"	"	1121	0	0	1141	0.3	$1661
Gas - 92%	Med	"	"	795	0	0	1021	0.3	$1308
GHP	Med	Vert	Typ	0	0	5726	1859	2.5	$827
"	"	"	Best	0	0	4775	1397	2.0	$736
"	"	"	Worst	0	0	6481	2382	3.3	$913
"	High	"	Typ	0	0	6390	2056	2.8	$880

Table 7. DOE-2.1E Performance Projections for SMUD

System Type	Load Case	Loop Type	GHP Case	Heating therms	Annual Usage (kWh) Clg	Htg	Misc	Peak kW	Annual Cost
Gas/AC-10 SEER	Med	N/A	N/A	361	2470	0	686	4.1	$972
Gas/AC-10 SEER	High	"	"	584	3636	0	1032	4.1	$1297
Gas/AC-12 SEER	Med	"	"	361	2065	0	686	3.5	$922
AHP-10 SEER	Med	"	"	0	2470	3824	729	4.1	$1087
GHP	Med	Vert	Typ	0	1747	1799	710	3.3	$800
"	"	"	Best	0	1247	1395	463	2.3	$687
"	"	"	worst	0	2774	2039	1051	4.8	$981
"	High	"	Typ	0	2792	3155	1195	3.5	$1099

For the SMUD service territory, projected GHP new construction savings are roughly $170/year vs. a standard Gas/AC system and $290/year vs. an AHP. The expected impact due to performance variations results in no savings for the "worst" case and savings of $280/year in the "best" case (vs. Gas/AC). As building loads increase, the expected annual savings increase slightly as the relative gas/electric utility rates in SMUD territory result in most of the savings occurring in cooling mode.

Economics

Economics were evaluated for each of the simulation cases using the total resource cost (TRC) method to calculate life cycle benefit-cost ratio (BCR). Evaluations assumed incremental GHP costs and utility incentives at three levels shown in Table 8. The mature market scenario can only be achieved if production volumes increase substantially, and if the installation infrastructure becomes fully developed.

Table 8. GHP Cost Assumptions

($/ton)	Current	Future	Mature
TDPUD			
Cost	$2600	$1200	$600
Incentive	$900	$200	$0
Net Cost	$1700	$1000	$600
SMUD			
Cost	$2100	$1200	$600
Incentive	$2100	$500	$200
Net cost	$0	$700	$400

A total of 29 economic configurations were evaluated with a variety of load, performance, and cost assumptions. Benefit-cost ratios and net utility revenues are provided in Table 9 for the four typical cases using current, future market, and mature market levels.

Table 9. Summary of Economic Results

	Benefit-Cost Ratio				Net Utility Revenue		
	Societal	Customer Perspective					
Case	**Perspective**	**Current**	**Future**	**Mature**	**Current**	**Future**	**Mature**
TDPUD	0.75	1.06	1.32	1.53	-$2179	$430	$1272
SMUD	0.94	1.18	0.92	1.02	-$4516	-$2117	$534

Cost effectiveness results indicate societal BCR's generally less than one. Customer BCR's are generally greater than one, especially in the "mature market" cost scenario of $600/ton. "Net utility revenue per site" - the difference between new utility revenue and life cycle cost over a 20 year period - is strongly negative for all current cost scenarios, and positive for all mature market scenarios.

Conclusions

Valuable products of this work included development of a standardized GHP monitoring methodology and validation of the DOE-2.1E ground loop model. Future GHP monitoring work can utilize this methodology and computer analysis can be completed with relative confidence in the results.

Other key project conclusions include:

1. No clear evidence of ground creep effects were observed over the two TDPUD heating seasons. Likewise, no creep was apparent from the SMUD monitoring which did not extend past a full 12 months.

2. GHP second stage heating was observed at only two sites and in both cases was less than 3% of total heating energy use.

3. Full-load monitoring data indicated an *average* response to entering water temperature and return air dry and wet bulb temperature consistent with published manufacturer's data.

4. DOE-2.1E projected typical SMUD demand savings (averaged over the 2-8 PM peak period) were ~20% (0.8-1.0 kW) vs. standard 10 SEER cooling equipment. Maximum projected TDPUD winter peak demand were expected to increase from 0.3 to about 2.5 kW relative to the standard 78% AFUE gas furnace.

5. Given current utility incentives, GHP's are currently viable in TDPUD service territory. In SMUD territory, GHP's are generally viable at future economics only vs. AHP, but not vs. Gas/AC systems. More favorable relative gas/electric rates in the TDPUD area are a large contributor to favorable economics.

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